AMRA CR 66-05/17

CENTER FOR HIGH ENERGY FORMING

FOURTEENTH QUARTERLY REPORT OF TECHNICAL PROGRESS

Jimmy D. Mote

January 1, 1969

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172

Martin Marietta Corporation
Denver Division
Contract DA 19-066-AMC-266(X)
The University of Denver
Denver, Colorado

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ABSTRACT

Checkout is continuing on the computer program for springback and mechanics of blank deformation.

Experimental studies on die design criteria are continuing.

Preliminary results on energy transfer in explosive welding are presented.

Additional data on strain rate effects is presented.

Preliminary designs of charge shapes for explosive punching of armor are discussed.

The work on explosive forming of rings is being extended to include experiments in large deformations.

The effort on electromagnetic and electrohydraulic forming will concentrate on theoretical analysis and design of meaningful experiments.

The experimental program on the effect of explosive forming on the terminal properties of materials is just beginning and the initial results are discussed.

The basic problems associated with explosive welding are described and a program for a more fundamental understanding of the phenomena is presented.

CONTENTS

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I. MARTIN MARIETTA CORPORATION

1. Springback and Mechanics of Blank Deformation

Principal Investigator: G. A. Thurston

Checkout is continuing on the computer program for calculating the dynamic plastic response of circular blanks to explosive charges. Preliminary output has been obtained from every subroutine in the program. This output is being checked for minor errors that prevent the iterative procedure from converging.

The format of output statements in our computer system has been changed since many of the subroutines were originally programmed. These statements are being rewritten to give more detailed output for checking individual subroutines. The statements for common storage are also being changed from numbered common statements to named common statements.

2. Die Criteria Developments

Principal Investigator: J. Mallon

The effect of various back-up materials on die shell behavior was indicated in the 13th quarterly by means of the average radial strain observed in a die shell. The general conclusion was that sand, wet sand, and contained water offered little improvement over the infinite water medium configuration.

Although results are not completely conclusive, it is logical to pursue die design configurations that embody the simple features of the infini' water back-up together with using direct die structure to resist the higher applied loads at the draw radius and at the bottom center of the die. A die of 12" diameter cavity opening, employing these features is presently being built and is shown in section in Figure 1.

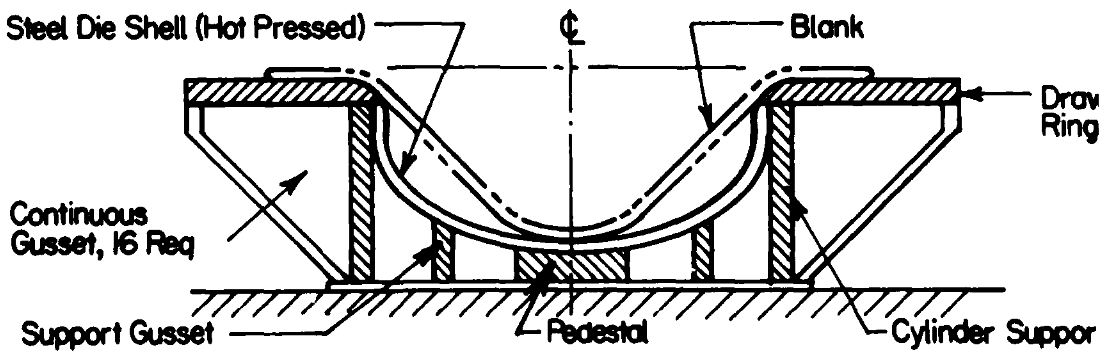


Figure 1

Schematic of Stiffened Die

It can be seen that water inundates the underside of the die shell and is relied on for absorbing energy in region where under structures is not provided. The pedestal reacts the high shock loads occurring at that point of the blank bottoming, and thus generates no membrane stresses in the die shell. The general features can be seen in Figure 2.

Figure 2

Stiffened Die Configuration

This die will be subjected to die cavity shock loads after which change in die shell contour and other measurements will be recorded.

3. Energy Transfer in Explosive Welding

Principal Investigator: W. E. Simon

One of the important problem areas in explosive welding is the relationships between explosive type and loading; cladder plate material properties and geometry; and the impact conditions onto the base plate. The goal of this work is a computational technique which will include the effect of a) cladder plate properties and geometry, b) buffer plate, c) explosive type, loading and standoff, and d) a cover plate and its standoff on the impact conditions. It will then be possible to compute the optimum configuration to produce any required impact conditions.

The first analysis developed used an elastic - work hardening representation of the cladder plate material and computed the air resistance on the bottom of the cladder plate with Modified Newtonian Flow equations. The result was that air forces were second order for any reasonable geometry, and that the material properties of the cladder plate were important only for the transient response of the

cladder plate (effectively a "ringing" superimposed on the response of the plate considered as a fluid). Therefore the current analysis considers only the density and mass of the cladder plate.

Now the detailed computation of the flow field of the detonation products would be complex and very expensive in computer usage, so the flow field was simplified to one dimensional flow of an ideal gas with the idea of adjusting the specific heat ratio to match experimental data on cladder plate deflection. As shown in Figure 3, the specific heat ratio is about three for most explosives at detonation pressures. Typically, the ratio drops to about 1.2 as the gas expands to atmospheric pressure. Note that the detonation pressure is not an independent variable, but can be computed if the explosive density, detonation velocity, and specific heat ratio are given.

Finally, for the case of explosive in contact with the cladder plate and no buffer or cover plate, only three parameters are required for the differential equation for the cladder plate deflection, a) explosive specific heat ratio, b) ratio of explosive density to cladder plate density, and c) ratio of explosive mass to cladder plate mass.

Figure 4 presents computations for a specific heat ratio of 2.25 with data from Carpenter for C-70 explosive. It is seen that the agreement is quite good for a value of the specific heat ratio which is a reasonable average for the expansion process.

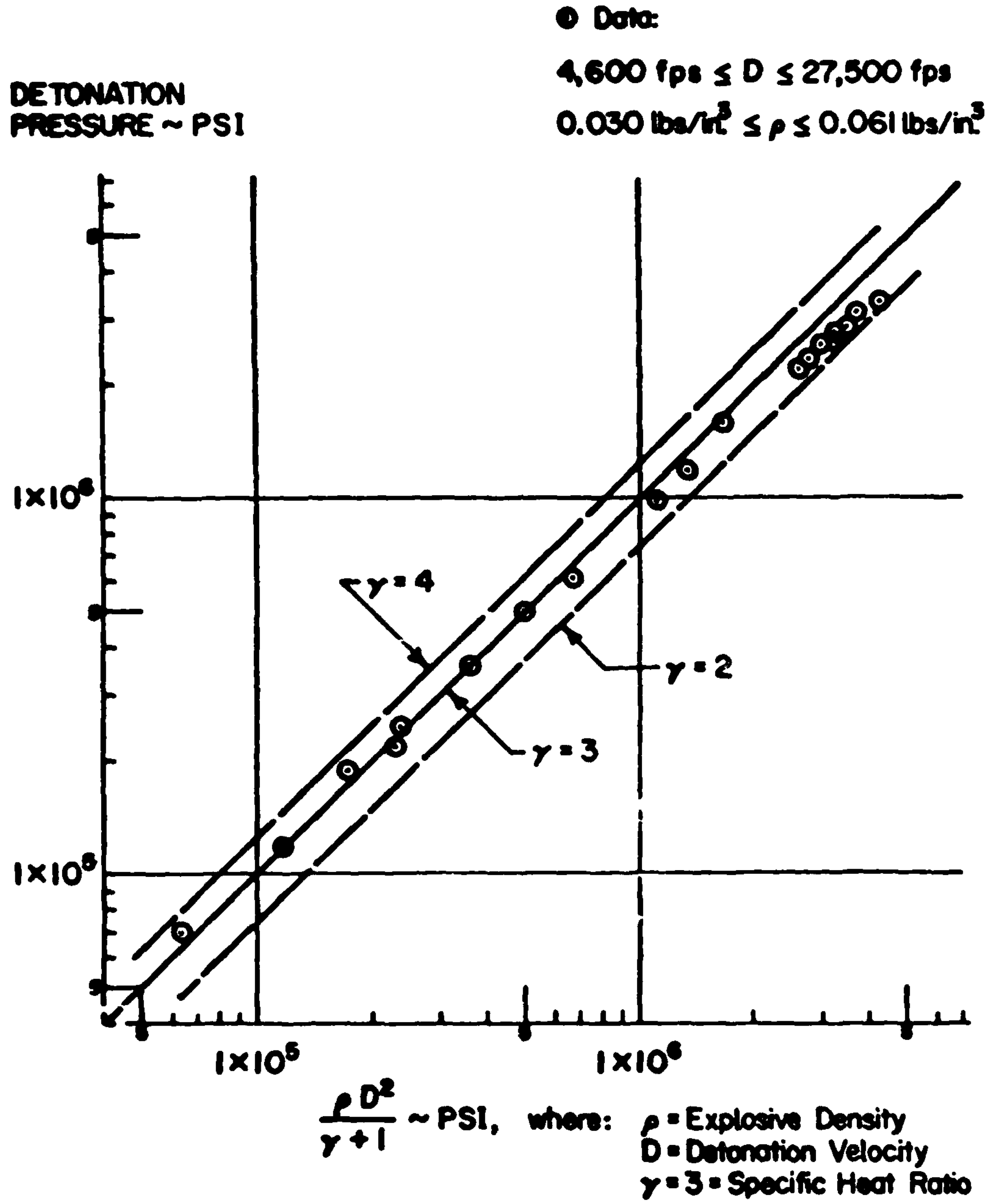


Figure 3. Correlation of Detonation Pressure with Specific Heat Ratio for Various Explosives

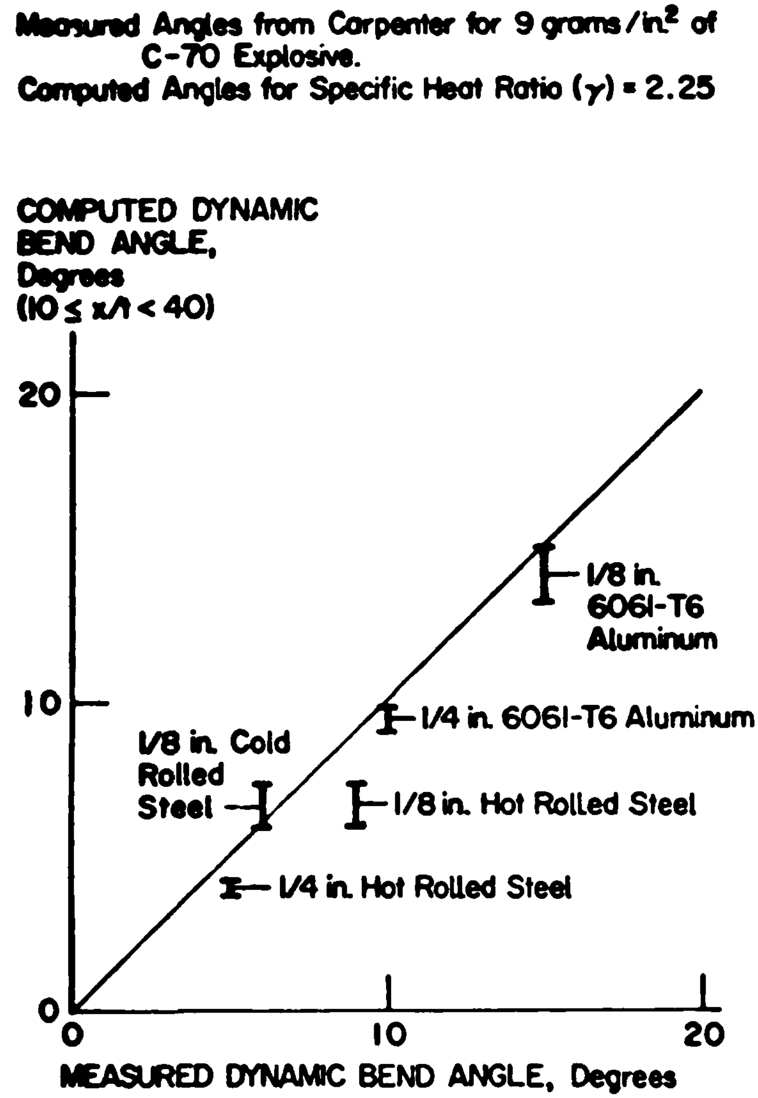


Figure 4. Comparison of Computed and Measured Dynamic Bend Angle

II. UNIVERSITY OF DENVER

1. Strain Rate Effects

Principal Investigator: C. Hoggatt

The dynamic stress-strain behavior of 4340 steel (quenched and tempered at 1025°F to produce a hardness of R_c 39) was determined using the expanding ring technique. This relationship which can be represented by a single dynamic curve is presented in Figure 1. Included on the figure is a tabular listing of the engineering mechanical properties of this steel for the specified heat treatment. In light of the fact that true stress values increase significantly over static engineering values as the strain is increased; it can be deduced from this figure that only a small strain rate effect exists for this material at larger strains, with a more significant effect occurring at lower strain values. It may also be observed that an increase in ductility of approximately 3.5 to 4.0 percent is obtained for the dynamic case.

Additional test data was obtained for the 6Al-4V-titanium alloy. The dynamic stress-strain curve presented for this material in the Twelfth Quarterly Report of Technical Progress, July 1, 1968, is therefore being resubmitted at this time. The curve has been modified slightly in light of this additional data and is presented in Figure 2. Here again, static engineering properties are tabulated on the plot for comparison purposes. As discussed in the earlier report, the strain rate effect for this material is quite pronounced, and can be observed in this figure. No increase in ductility was observed for this material as a result of dynamic deformation behavior.

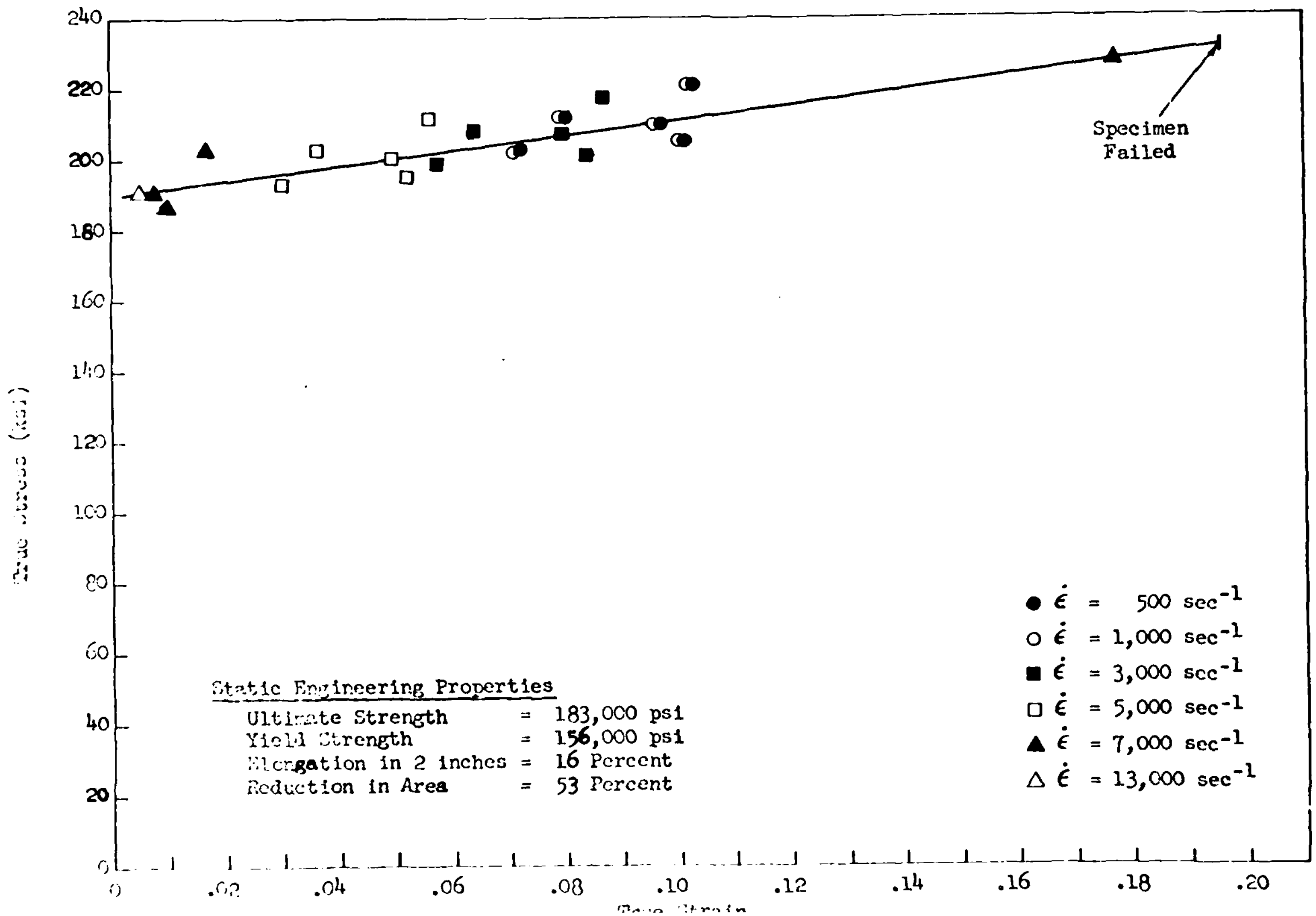
Specimens of 4130 steel are presently being machined in preparation for dynamic property determinations. Initial tests will be conducted on specimens heat treated to a hardness level commensurate with the hardness of the 4340 specimens (R_c 39-40).

2. Explosive Forming and Punching of Dual Hardness Armor

Principal Investigator: W. Howell

The objective of this program is to develop techniques for explosive hole punching in dual hardness armor. The technique to be developed is to produce holes of a controlled dimension without spalling or petalling and which require little or no subsequent finishing.

The basic principle being applied is the focusing effect produced by a cavity i.. an explosive charge. In one shaped charge design used most frequently the cavity is an axially symmetric cone with a thin



True Stress (ksi)
240
220
200
180
160
140
120
100
80
60
40
20
0
True Strain
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
Specimen Failed
Static Engineering Properties
Ultimate Strength = 183,000 psi
Yield Strength = 156,000 psi
Elongation in 2 inches = 16 Percent
Reduction in Area = 53 Percent
$\dot{\epsilon}$ = 500 sec^{-1}
$\dot{\epsilon}$ = 1,000 sec^{-1}
$\dot{\epsilon}$ = 3,000 sec^{-1}
$\dot{\epsilon}$ = 5,000 sec^{-1}
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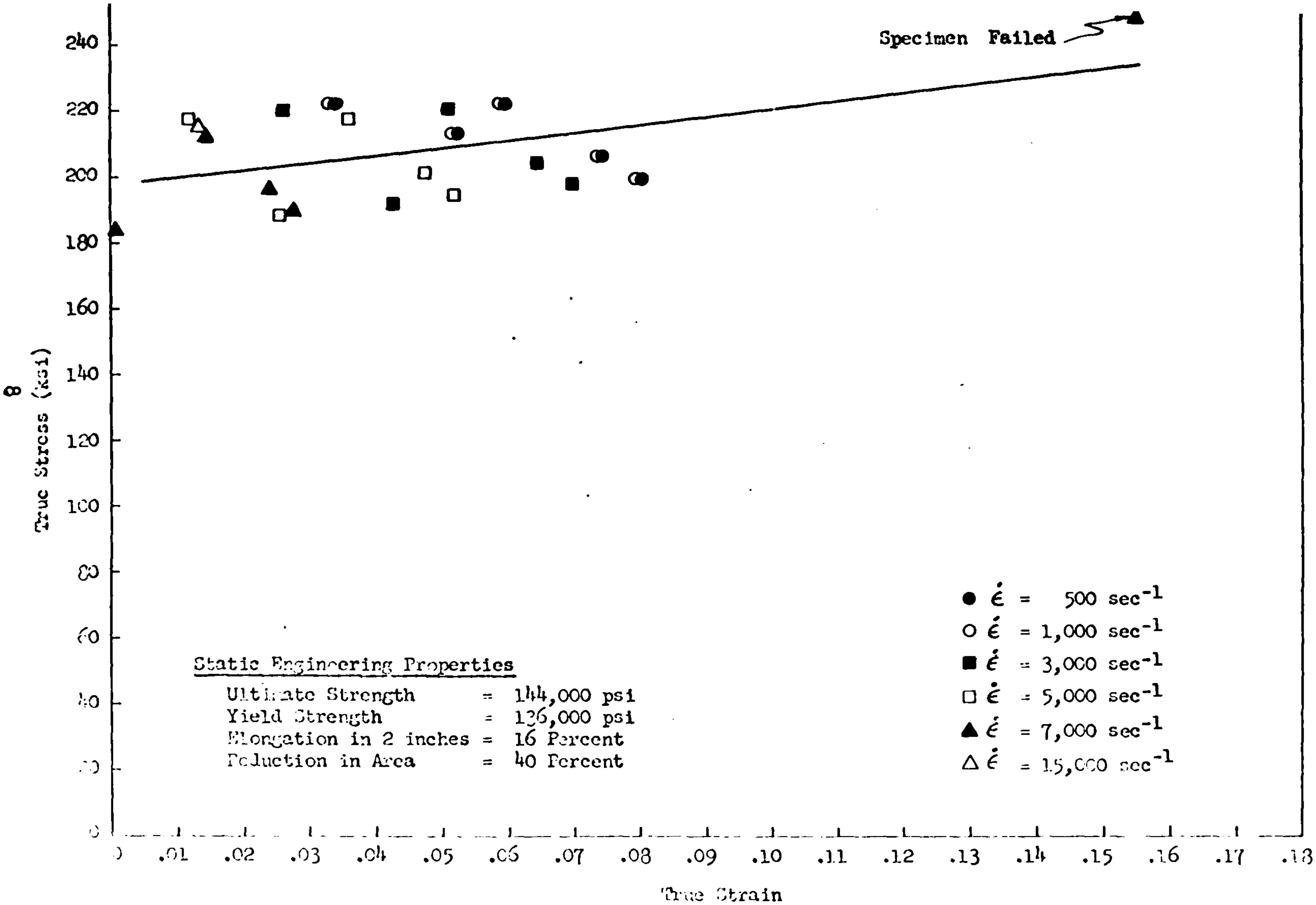

Figure 2. Dynamic Stress-Strain Curve for 6Al-4V-Titanium.

metal liner in a cylindrical charge. The explosive charge is detonated at a point above the apex of the cone. As the detonation front moves toward the base of the cone the high pressure of the detonation products collapse the metal liner upon itself forming a hypervelocity jet which moves ahead of the detonation front along the axis of the cone. When this jet impinges on the target material the pressure created greatly exceeds the strength of the steel and penetration takes place by a hydrodynamic process. A shaped charge design which has been used extensively for explosive cutting is the linear shaped charge. Here the liner is a "V" shaped trough, the convex side of which is backed by explosive. The linear shaped charge is usually initiated from one end; the detonation front proceeds along the length of the charge and the jet is propelled at some angle other than normal to the longitudinal axis of the charge.

The design approach being used on this program combines certain features of the two designs described above. In this design, the "V" shaped trough which is characteristic of the linear shaped charge is formed into a ring, the circumference of the ring (measured at the apex of the "V") being slightly under the size of hole to be cut. The explosive ring is initiated at the apex of the "V" simultaneously around the circumference to assure a vertically acting jet. This is accomplished by using a line wave generator which makes contact all around the circumference at the apex of the "V" shaped trough. The jet which is formed may be thought of as a thin cylindrical sheet which has the affect of a cookie cutter. A back up die is used to minimize spallation and deformation. The shaped charge is designed to cut part way through the plate and a centrally located secondary charge is used to provide sufficient over pressure to finish shearing the plug out of the plate. This concept is illustrated schematically in Figure 3.

To evaluate this concept the initial design was for a shaped charge to cut a two-inch diameter hole in one-half inch, high strength steel plate. A die for forming the liner was made using an included angle of 90 degrees and a leg length of 0.3 inch. The explosive used most effectively was composition C-2 Detasheet formed to fit the liner. To date it has been established that this hole punching technique is effective in punching a two-inch hole in one-half inch thick mild steel plate and in 3/8-inch thick hardened steel plate. A fairly clean hole is punched without spallation. Techniques for improving the quality of the hole and for evaluating other ratios of plate thickness to hole size are being developed.

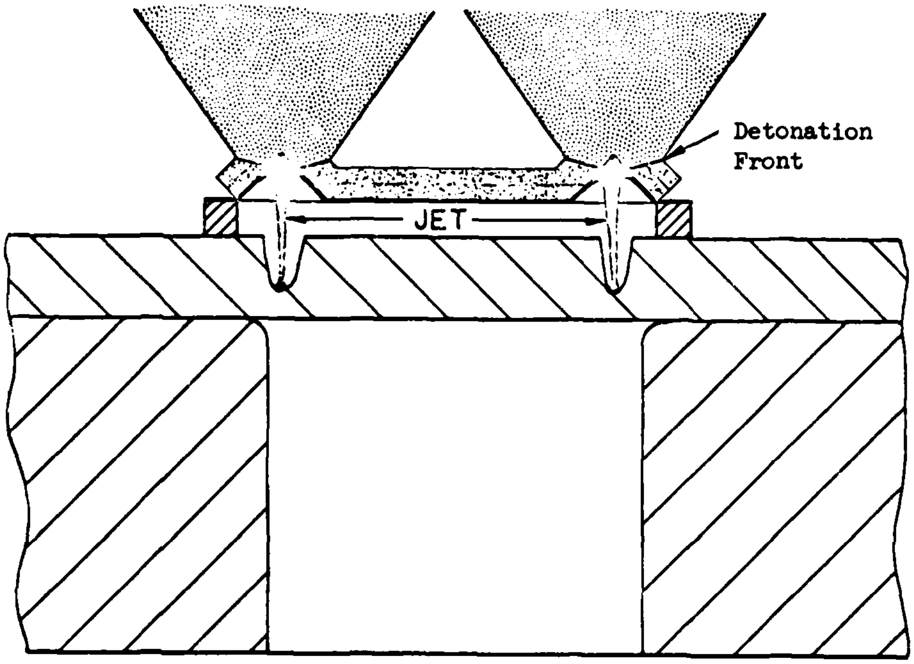

Figure 3. Representation of Explosive Hole Punching During Jet Formation and Penetration.

3. Mechanics of Energy Transfer and High Velocity Metal Deformation

Principal Investigators: J. A. Weese, M. Kaplan, A. A. Ezra

Graduate Students: M. Nguyen, H. Bodoroglu, G. Ney, S. Kulkarni

The work on explosive forming of rings is now being extended to include experiments in large deformations. Work is just emerging from the literature survey stage in two new areas: attenuation of shock waves by bubble curtains which is the thesis project of Mr. Ninh Nguyen, and the buckling of an elastic-plastic annulus (flange wrinkling) which is the thesis project of Mr. H. Bodoroglu. Mr. Gordon Ney now has the bongo drum ready for preliminary shots to measure efficiency of energy transfer. Trouble with instrumentation has slowed the project.

Mr. S. Kulkarni is proceeding with the development of a simplified analytical model of the strain energy of a dome including the effect of edge pull in. This approach is based on solving for edge pull in by minimizing the total energy of deformation of both flange and dome with respect to edge pull in. The analysis includes the magnitude of the hold down force, the friction between flange and die, the radius of curvature of the die entry, as well as the blank and die dimensions and blank material properties.

4. Electromagnetic and Electrohydraulic Forming

Principal Investigator: William N. Lawrence

Graduate Student: Lloyd E. Gilbert

During the fourth quarter of 1968 the Graduate Research Assistant in magnetic forming, Lloyd E. Gilbert, finished his thesis and his other requirements of the degree Master of Science.

Lloyd's thesis topic was on the mechanical design aspects of forming coils. His work included a literature survey, theoretical design and experimental confirmation of his design calculations. He has accepted a position with Martin Marietta in Denver.

The theoretical aspects of the thesis emphasized the need for a better understanding of the dynamics of the magnetic forming process. A rather extensive description of electrical dimensions has been drawn up and used to develop a dimensional analysis of the process. In addition, considerable work has been done on the calculation of energy transfer and the efficiency of the forming operation. Preliminary results indicate that an efficiency of 15% for small parts is acceptable, but the efficiency may be increased for large parts by a factor of roughly two.

In addition to the above endeavors, a paper was presented at the

Upper Midwest ASTME Conference and the capacitor bank enclosure was installed, including mechanical interlocks, door interlocks, etc., to prevent inadvertent access to hazardous areas.

During the next quarter, progress will be slowed greatly because of the loss of the experienced assistant and the fact that the principal investigator will spend only about one quarter time on the project. Effort will be directed to theoretical analysis and the design of meaningful experiments to verify conclusions.

5. Fracture Toughness Testing of High Strength Low Alloy Steels

Principal Investigator: H. Otto

Graduate Students: R. P. Mikesell and C. Yin

The forming of the 4130 and 4340 steels is being conducted by the Martin Company. The flat bottom die did require reworking after the first dome of 4130 was made. Seals had to be added to maintain a vacuum. In the one dome that has been formed a hardness increase of from 180 to a maximum of 237 Bhn was noted. Although the grid was lost in several areas, enough of the pattern remained in the center portion to measure the strain. A variable strain pattern was obtained which varied from about 8% at the immediate center of the dome to about 16% at a distance of about 30 to 40 mm from the center. The maximum strain corresponded roughly to the edge of the contact explosive area.

Heat treatments are underway on as-received stock to establish quenching procedures and drawing temperatures. Coupons of the explosively-formed stock have also been heat treated for comparison purposes. The actual fracture toughness testing of as-received stock will be initiated in the near future. Pop-in tests corresponding to those conducted by the Martin Company will be used so all testing procedures on the program will be uniform.

Some explosively-formed HY 80 steel has been received from North American Rockwell and will be incorporated with the above program.

6. Stress Corrosion Cracking Susceptibility of Explosively and Conventionally Formed 2014 Aluminum Alloy

Principal Investigator: R. N. Orava

Graduate Student: G. S. Whiting

The present studies of the relative effects of explosive and conventional forming on the stress corrosion cracking susceptibility of 2014 aluminum alloy are near completion. The investigation is concerned with material formed in the O condition

followed by a T6 tempering heat treatment (Martin Company specifications) and with material formed in the T6 condition followed by no thermal or hardening treatment.

The two forming methods, which have been used to form 12-in. diameter domes from 1/8 in. thick 2014-0 and Alclad 2014-T6 plate, are free forming explosively and rubber pressing at a very low rate. Specimens with comparable effective strains for bent-beam stress corrosion studies have been selected from the explosively and slowly formed domes. Control coupons have also been included in all these studies: 2014-0 control coupons heat treated and tempered to the T6 condition; Alclad 2014-T6 control coupons with the Alclad stripped (as has been done to dome specimens of Alclad 2014-T6).

Samples have been exposed to a 3.5% NaCl solution at ambient temperature by alternate immersion (10 min. in solution, 50 min. drying in air) at either 75% or 90% of the macroscopic T6 yield stress for periods of 30 or 15 days. All of the exposed specimens have been sectioned and are being polished and examined at 200X for intergranular stress corrosion cracks. The arbitrary criterion chosen to determine relative effects due to the two forming methods is the maximum crack length.

Domes from Alclad 2014-T6 material with the desirable effective strains have recently been free formed explosively and such specimens are being prepared for stress corrosion testing.

Future plans with respect to the indicated materials are (1) to produce curves of strain versus thickness for three or four domes, (2) to examine the substructure by transmission electron microscopy of the like conditions of 2014 alloy which have been investigated for stress corrosion cracking susceptibility, and (3) to conduct tensile tests on a few "flattened" specimens from rapidly and slowly formed domes of 2014-0 material.

7. A Comparison of the Terminal Fatigue Properties of Isostatically and Explosively Formed Domes

Principal Investigator: H. Otto

Graduate Student: R. P. Mikesell

Aluminum 2014 is the first alloy that has been under investigation. The parent, or unstrained, material has been tested in order to establish consistency in data with the following test parameters: (1) geometry of samples, (2) heat treatment, (3) surface preparation of the samples, (4) the test machine, and (5) the applied stress. The specimen is 1/8" thick, 3-5/8" long, and has a middle section which is gradually reduced from the ends to a 1/4"

wide center in a 1-3/4" radius. Material formed in the annealed condition has been heat treated to the T6 state according to Martin Company specifications. Each sample has been hand ground with 240, then 400, and finally 600 grit paper. The specimens are then electropolished in a methanol-nitric acid-hydrochloric acid solution below 15°C. The time of polish is long enough to remove the thin compression layer that results from the grinding operation. Testing is done in uniaxial tension-tension on a Marquardt Universal test machine. Oscillations are accomplished with a sine-wave function generator; the highest stable frequency of the machine is 10 cps. Load on the sample is read on a calibrated oscilloscope. Each specimen is placed in the grips in the same manner and a small preload is applied in order that the sample be self aligned. An applied stress of 50,000 ± 14,500 was chosen. With these test conditions, the results on the 2014-T6 (Martin treatment), orientation in the longitudinal direction were found to be the following:

Fatigue Life of Specimens Taken with Longitudinal Orientation, cps

244,500	204,000
96,000	171,000
314,500	120,000
498,000	156,000
96,100	120,000

Ave. (10) = 202,000 cps

The third and fourth values deviate from the other data, but in the basis of standard deviation, the results are reasonably consistent for fatigue tests.

Having noted that fatigue results were consistent, testing of samples cut from the isostatic and explosive formed domes has been initiated. Comparison is being made on the basis of effective strain and orientation. Samples cut from each type of dome are straightened in the same manner: each specimen is cooled to dry ice temperature and then straightened in a vise without disturbing the center of the specimen. Thus, samples from the explosive and isostatic domes can be compared directly since the domes have been subjected to the same stress state and the samples have been prepared in the same manner.

Two samples have been tested from an isostatic dome:

Sample	Effective Strain	Orientation	Fatigue Life
F1	30%	Rolling Direction	180,000 cycles
F6	26.4	45° from R.D.	144,000

More data would have been presented to date on dome samples. However, it was found that cracking occurred in the strained samples due to chloride contamination in the heat treating salt bath. This problem has been corrected and more specimens are being prepared.

8. Microstructure of Explosively Formed Metals

Principal Investigator: L. F. Trueb

Graduate Student: P. K. Khuntia

The microstructures of 2014 aluminum, 50A titanium and 6Al4V titanium are being investigated by transmission electron microscopy and electron diffraction after explosive and static forming. The objective of this study is to accurately characterize the specific effects of high-energy deformation on the lattice defect substructures and the response of the latter to heat treatment.

1. 2014 Al. Both explosively and statically formed material is presently available in the O-condition. A preparation method of this material for electron microscopy has been developed: it consists of mechanical wetting, chemical etching and final electrolytic polishing. The present program for this material is to study the solution heat treatment response of formed 2014-O, the overaging response of formed 2014-T6, and thermal recovery and recrystallization in both cases.

2. 50A Ti. The material has been cold rolled and explosively as well as statically formed into domes. A special furnace for heat treating the material in ultra-pure argon has been designed and is presently being tested. A chemical polishing method has been found suitable for preparing the thin films required for electron microscopy. The microstructural investigation will concentrate on early stages of thermal recovery and recrystallization in an effort to compare the behavior of material subjected to monoaxial and biaxial static deformation and to explosive forming.

3. 6Al4V Ti. The material is presently being readied for explosive and static deformation. Microstructural studies will be similar to those outlined for 50A titanium, with a special accent on the martensitic transformation occurring in this material.

9. Explosive Welding

Principal Investigator: S. Carpenter

Graduate Student: B. Winchell

The explosive welding research has been concerned with the spin off contracts and further development of the basic parameters involved in explosive welding. One contract, involved with the welding

of Ti6Al4V sheet and stringers has demonstrated the need for more basic knowledge concerning the materials and geometries used for fixtures. Pressure wave interactions between the supporting fixture and the stock to be welded determine the success of the process. Surprisingly, hardened steel fixtures actually prevented welding, whereas mild steel dies were conducive to welding. Other spinoff programs are concerned with the welding of lead to steel and welding and repair of pipe.

The basic welding parameters presently used in explosive welding are empirically derived and are not dimensionally correct. These parameters are also limited by the thickness of the material. More basic knowledge of the reaction at the interface is required. Universal factors include the pressure and temperature developed during welding. The present program is concerned with means to measure the pressure pulse and correlate this with the type of weld obtained. Passive pressure gages are being made and calibrated for these measurements at the present time. Another portion of the program has been concerned with welding laminates, for turbine applications. Again, weld geometries are of prime importance to prevent closure of air passages in the laminate.

Future work will be concerned with developing a better understanding of the inter-relationship between the various welding parameters and how these parameters can be extended to various configurations.

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Ductility						
Die Design						
Strain Rate Effects						

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